DYNAMIC LOAD MITIGATION OF TRIPLY PERIODIC MINIMAL SURFACE STRUCTURES BASED ON GRADIENT DESIGN

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ABSTRACT

Triply periodic minimal surface (TPMS) has a mathematically controlled geometric topology and excellent physical and mechanical properties that are of great value in impact protection. In this work, a functionally gradient design based on the IWP lattice structure is proposed to obtain four structures with varying relative density gradients. The dynamic compressive mechanical properties of uniform and gradient IWP structures under the impact velocity of 20 m/s are analysed by numerical methods, combining JC plastic and damage models to describe the mechanical responses of the structures at high strain rates. A variety of indicators are used to evaluate the mechanical properties. In particular, the SEA of the gradient structure is improved compared to the uniform structure. The results show that the gradient variation strategy of relative density has positive applications for improving the mechanical properties of TPMS structures and increasing their energy absorption capacity.

1 INTRODUCTION

In the field of impact resistance and energy absorption, the design of new impact resistant structures and the research of impact resistance has been a popular issue of concern. In recent years, lightweight porous materials have been widely used due to their high porosity, high specific strength and stiffness as well as excellent energy absorption, heat exchange and impact resistance [1-4]. The limited control of internal cavities and unavoidable manufacturing defects in conventional foams easily cause unstable mechanical properties, which is a challenge for their wide application. Typical lattice structures usually consist of truss rods and nodes. The nodes are susceptible to stress concentrations during bearing, which can cause damage to the structure. Consequently, the structural design and mechanical properties of new lightweight porous materials are of high scientific significance and application value in the field of structural impact and protection.

Triply periodic minimal surface (TPMS) structures have attracted much attention for their mathematically controllable topological configurations and excellent mechanical properties. TPMS has a smooth surface with no sharp edges, thus avoiding stress concentrations. TPMS has a smooth surface with no sharp edges, which helps to avoid stress concentrations. In addition, TPMS structures have high porosity, high specific surface area, high specific strength and stiffness as well as excellent energy absorption and fatigue resistance [5]. Functional gradient structures are a kind of advanced engineering materials that are designed to achieve specific functional and mechanical performance requirements. They are able to control the properties of the lattice structure through gradient changes in the structural cell. Therefore, in this work, a typical structure (IWP) of TPMS is investigated, incorporating the design idea of functional gradients. The aim is to investigate the effect of relative density gradient changes on the mechanical behaviour of IWP structures under dynamic impact loading.

2 STRUCTURE DESIGN

2.1 Design method

Mathematically, minimal surface is a surface with zero mean curvature at any point. It has connected apertures and continuous, disjoint surfaces. There are several methods available for generating minimal surface structures, such as the Weierstrass parametric equation [6-7] and the general equation for periodic surfaces. Based on the second method, the IWP structure is established using an implicit function equation consisting of the trigonometric functions:

$$\Phi_{IWP} = 2(\cos X\cos Y+\cos Y\cos Z+\cos Z\cos X) - (\cos 2X+\cos 2Y+\cos 2Z) = C \quad (1)$$

where $X=2\pi x/l$, $Y=2\pi y/l$, $Z=2\pi z/l$, l is the length of the unit cell in x, y, z directions, and the constant C controls the offset of the surface. Figure 1(a) shows the shell cell model of IWP unit cell, and the size of the unit cell is 7mm×7mm×7mm. The lattice structure of IWP shown in Fig. 1(b) is obtained by arranging the unit cell periodically in a spatial coordinate system along the x, y, z directions. The number of cells in the lattice structure is 3×3×5 and the dimension is 21mm×21mm×35mm.

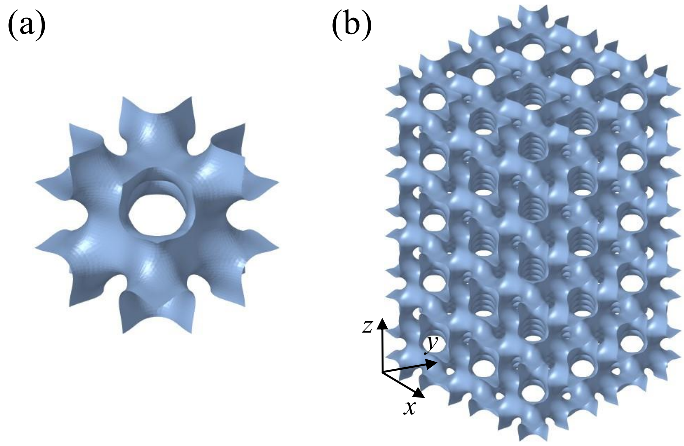


Figure 1: (a) unit cell of IWP, (b) lattice structure of IWP

2.2 Relative density gradient design

Figure 2(a) shows four designed gradient IWP structures and one uniform IWP structure. The relative density of the uniform IWP (UN) structure is 37.5%, and the relative densities of gradient IWP lattice structures vary along the z-axis in the range from 30% to 45%. There are two types of structures with linear gradients of relative density, the LG1 structure, which increases uniformly from 30% to 45% along the z-axis, and the LG2 structure, which decreases uniformly from 45% to 30%. There are two types of structures with piecewise functions of relative density. There are the PF1 structure, which varies linearly along the z-axis from 30% to 45% and then decreases to 30%, and the PF2 structure, which varies linearly along the z-axis from 45% to 30% and then increases to 45%.

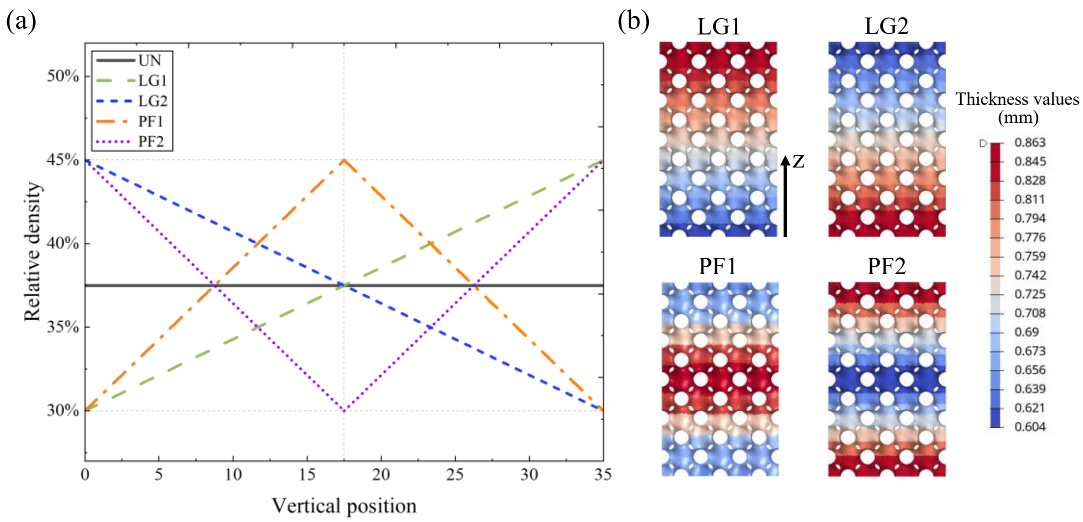


Figure 2: (a) relative density distribution on IWP, (b) thickness distribution in z-direction

In this work, the relative density is controlled by defining the thickness of the shell structures. Figure 2(b) shows the four gradient IWP structures for distribution of shell unit wall thicknesses. For IWP structures, the relative densities of 30%, 37.5% and 45% correspond to shell thicknesses of 0.587, 0.734

and 0.881, respectively. For LG1 and LG2 structures, the relationship between wall thickness T and structure height z is given by the following equations:

$$T_{LG1}=21/2500*z+0.587,\ 0\leq z\leq 35 \tag{2}$$

$$T_{LG2}=-21/2500*z+0.881,\ 0\leq z\leq 35 \tag{3}$$

For PF1 and PF2 structures, the relationship between wall thickness T and structure height z is given by the following equations:

$$T_{PF1}=\begin{cases}21/1250*z+0.587, 0\leq z\leq 17.5\\ -21/1250*z+1.175, 17.5\leq z\leq 35\end{cases} \tag{4}$$

$$T_{PF2}=\begin{cases}-21/1250*z+0.881, 0\leq z\leq 17.5\\ 21/1250*z+0.293, 17.5\leq z\leq 35\end{cases} \tag{5}$$

3 NUMERICAL SIMULATION AND ANALYSIS

3.1 Finite element model

In this paper, ABAQUS/Explicit 2021 is used to complete the finite element simulation of the dynamic compression mechanical properties of the IWP structures. The finite element model of the structures under impact loading is shown in Figure 3(a). The sandwich core is the gradient IWP structure designed in this paper, and the upper and lower planes are rigid plates. The upper plate can only move along the z-axis with an applied velocity of 20 m/s, and all degrees of freedom of the lower plate are constrained. The mesh size is 0.4 mm, the cells are triangular and the number of meshes obtained is 110306. The IWP structure uses the first order three node shell (S3R) cells and two discrete rigid panels using R3D4 cells with compression strain set to 0.8.

The Johnson-Cook plastic and damage model was used to describe the plastic deformation and damage behavior of the structure. JC model is widely used to study the dynamic mechanical response of materials under impact loading. The parameters of the JC plastic and damage models used in this paper are shown in Tables 1 and 2.

Table 1: JC intrinsic model parameters

Parameter	E(GPa)	v	ρ(t/mm^3)	A(MPa)	B(MPa)	n	m	C	$\dot{\varepsilon}$
Value	55	0.3	2.8E-9	210	230	0.4	0.859	0.015	0.001

Table 2: JC damage model parameters

Parameter	d_1	d_2	d_3	d_4	d_5
Value	0.0261	0.263	0.349	0.147	16.8

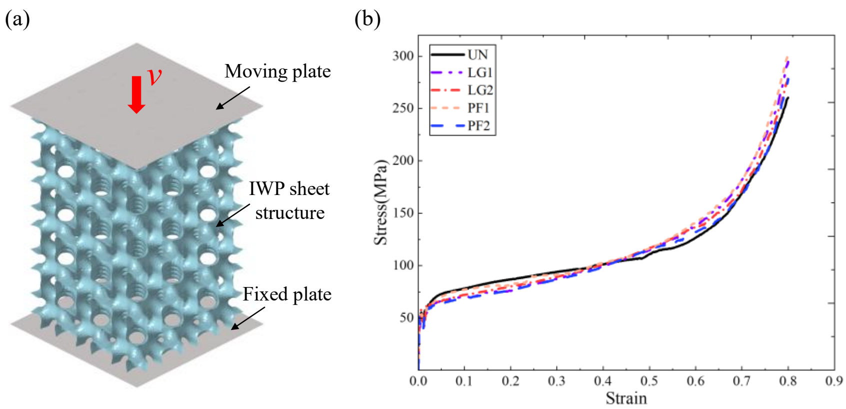


Figure 3: (a) finite element model, (b) stress-strain curve at 20 m/s

The force and displacement of the upper compression plate are extracted and the stresses and strains are calculated using the following equations:

$$\sigma = \frac{F}{A_0} \tag{6}$$

$$\varepsilon = \frac{\Delta L}{L_0} \tag{7}$$

where F is the force applied to the structure in compression, A_0 is the initial cross-sectional area of the structure, ΔL is the compression displacement and L_0 is the initial height of the structure in the direction of compression. Figure 3(b) shows the simulated stress-strain curve of the gradient structure at an impact velocity of 20 m/s with three typical stages: linear stage, plateau stage and densification stage.

Four types of parameters are used to evaluate the mechanical performance of the structure, namely specific energy absorption (SEA), mean crash force (MCF), peak crash force (PCF) and crush force efficiency (CFE). The definitions are shown below:

$$SEA = \frac{\int_0^{S_{ef}} F(x)dx}{M} \tag{8}$$

$$MCF = \frac{\int_0^{S_{ef}} F(x)dx}{S_{ef}} \tag{9}$$

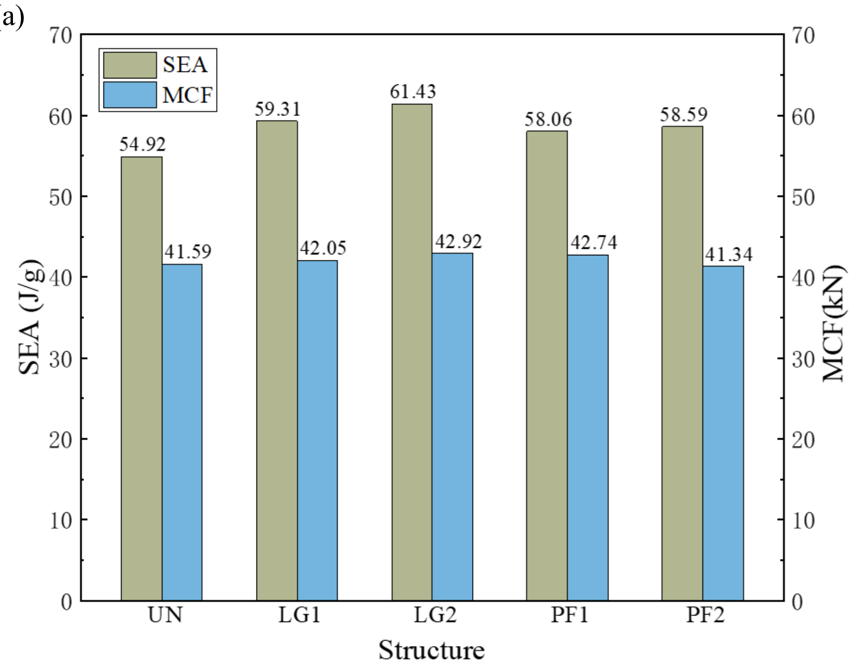
$$CFE = \frac{MCF}{PCF} \times 100\% \tag{10}$$

Where S_{ef} is the compaction displacement, which represents the compression displacement corresponding to the turning point of the structure from the plateau stage to the densification stage. PCF is the maximum value of the force in [0, S_{ef}], and M is the mass of the structure and $F(x)$ is the compression force.

3.2 Analysis and discussion

Based on the structural stress-strain curve, the four evaluation indicators calculated are shown in Figure 4. As can be seen from Figure 4(a), the SEA of all four gradient structures is higher than Uniform structure, and LG2 has the highest SEA. MCF reflects the load-bearing capacity of the structure in the plastic plateau, and the MCF of LG1, LG2 and PF1 is better than UN.

(a)



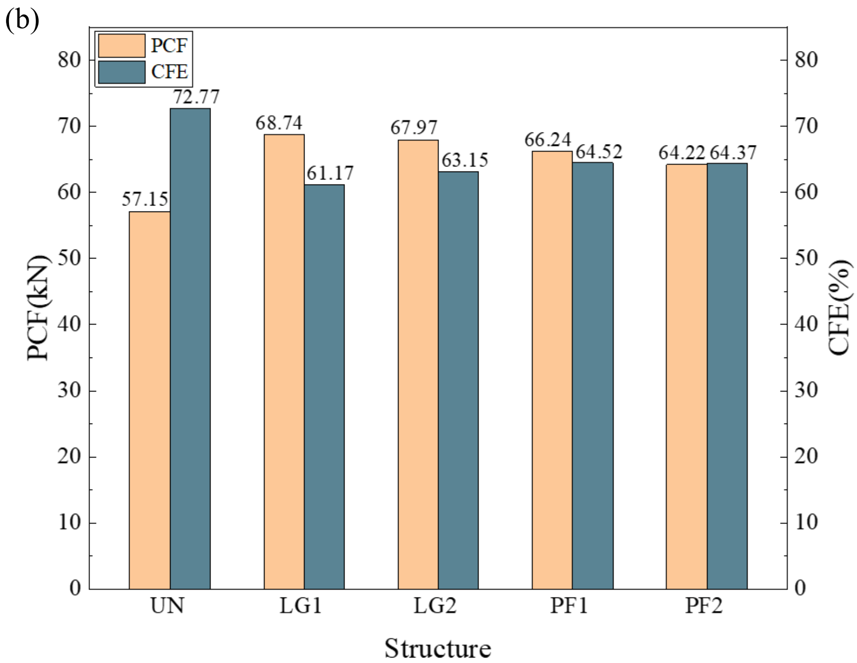


Figure 4: (a) SEA, MCF and (b) PCF and CFE of gradient and uniform structures

As can be seen from Figure 4(b), the PCF (the smaller the value the more favourable) and CFE of the gradient structure do not compare favourably with the uniform structure. The above analysis shows that the functional gradient design does not improve the overall mechanical properties of the structure. As far as the SEA of the structure is concerned, the gradient design can significantly improve the energy absorption capacity of the structure and has some research value in the design of multifunctional structures.

4 CONCLUSIONS

In this paper, a relative density gradient design is proposed based on the IWP structure, and the mechanical properties of the structure under impact loading are analyzed using numerical simulations, the following conclusions were obtained:

(1) Equating the relative density gradient of the structure to a wall thickness gradient change, the deformation of the gradient structure occurs first in the low-density region.

(2) The SEA of four gradient IWP structures is better than the uniform structure, where the MCF of LG1, LG2 and PF1 is also improved, indicating that these structures have better load-bearing capacity in the plastic stage.

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